CHAPTER 4
FMECA METHODOLOGY

4-1. Methodology – moving into Criticality Analysis

The FMECA is composed of two separate analyses, the FMEA and the Criticality Analysis (CA). The FMEA must be completed prior to performing the CA. It will provide the added benefit of showing the analysts a quantitative ranking of system and/or subsystem failure modes. The Criticality Analysis allows the analysts to identify reliability and severity related concerns with particular components or systems. Even though this analysis can be accomplished with or without failure data, there are differences on each approach which are discussed in the following sections. Figure 4-1 shows the process for conducting a FMECA using quantitative and qualitative means.

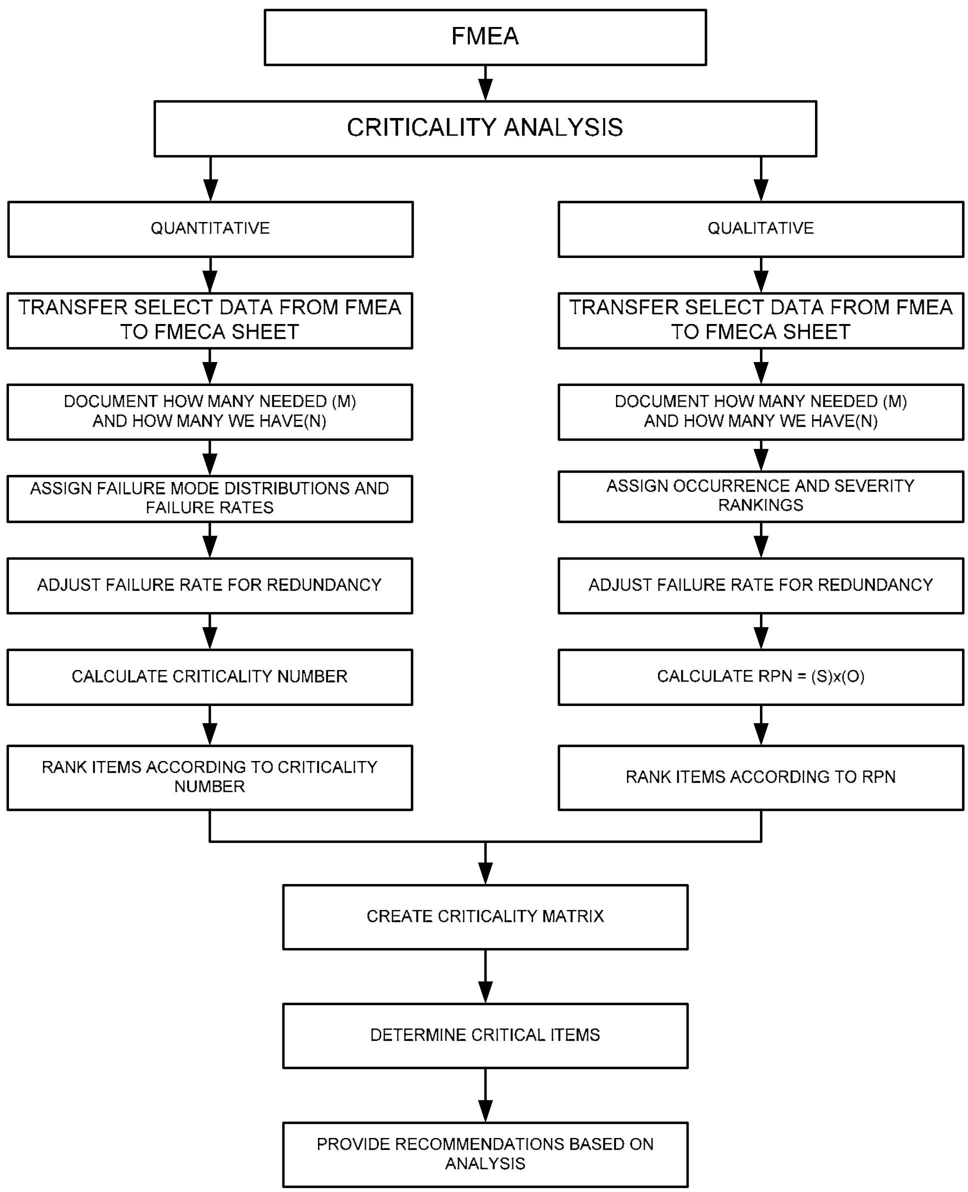

Figure 4-1. FMECA flow

4-2. Criticality Analysis

The Criticality Analysis (CA) provides relative measures of significance of the effects of a failure mode, as well as the significance of an entire piece of equipment or system, on safe, successful operation and mission requirements. In essence, it is a tool that ranks the significance of each potential failure for each component in the system's design based on a failure rate and a severity ranking. This tool will be used to prioritize and minimize the effects of critical failures early in the design.

a. The CA can be performed using either a quantitative or a qualitative approach. Figures 4-2 and 4-3 identify the categories for entry into their respective CA using DA Forms 7611 and 7612, respectively. Availability of part configuration and failure rate data will determine the analysis approach. As a general rule, use figure 4-2 when actual component data is available and use figure 4-3 when no actual component data or only generic component data is available.

b. Figure 4-4 is a representation of the different levels of data that a facility may have. Depending on the level of data available, the analysts must determine which approach they will use for the CA. The areas where there are overlaps between quantitative and qualitative, the analyst will have to assess what the expectations are for conducting the analysis to determine which approach will be used.

QUANTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)
For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System

DATE (YYYYMMDD): 20050819

PART NAME: Industrial Water Supply

SHEET: 1 of: 2

REFERENCE DRAWING:

COMPILED BY: AAA

MISSION: Provide Temperature Control to Room

APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNCTIONAL ID	POTENTIONAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	SEVERITY	REDUNDANCY		FAILURE RATE λ_p (SOURCE)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (C_m)	ITEM CRITICALITY NUMBER (ΣC_m)	REMARKS
					HAVE (N)	NEED (M)							

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Figure 4-2. Example of DA Form 7611, FMECA worksheet – quantitative

QUALTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System | DATE *(YYYYMMDD)*: 20050819

PART NAME: Industrial Water Supply | SHEET: 1 of: 1

REFERENCE DRAWING: | COMPILED BY: AAA

MISSION: Provide Temperature Control to Room | APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNC-TIONAL ID	POTENTIAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	FAILURE EFFECTS	SINGLE COMPONENT			REDUNDANT SYSTEM					REMARKS AND/OR RECOMMENDED ACTIONS
					OCCUR	SEVER-ITY	RPN (O)X(S)	HAVE (N)	NEED (M)	OCCUR	SEVER-ITY	RPN (O')X(S)	

DA FORM 7612, AUG 2006 | APD V1.00

Figure 4-3. Example of DA Form 7612, FMECA worksheet – qualitative

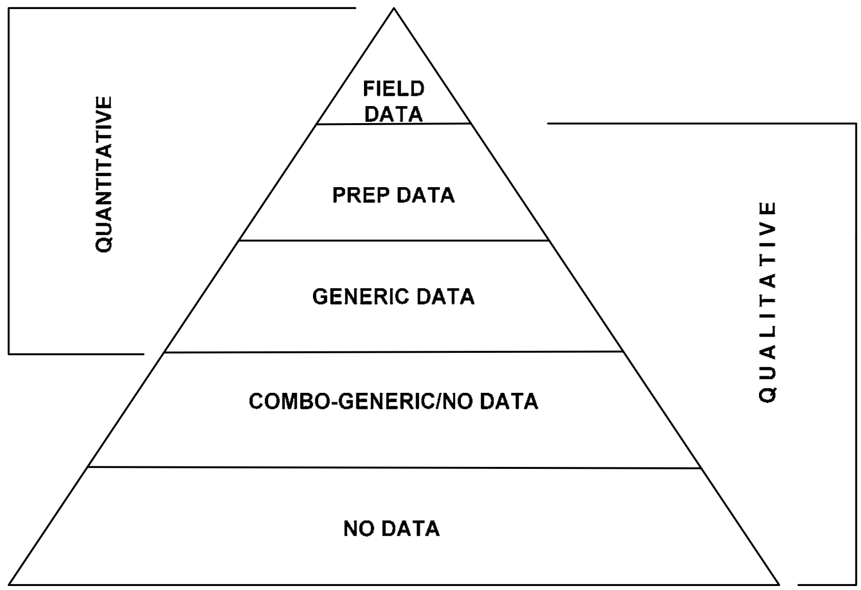

Figure 4-4. Data triangle

(1) Quantitative method is used when failure rates, failure modes, failure mode ratios, and failure effects probabilities are known. These variables are used to calculate a "criticality number" to be used to prioritize items of concern. This is used typically after the design has been completed when confident data on the system can be collected. However, in certain instances data may be available from other sources. This type of analysis will provide concrete figures which can be used for other types of analyses including fault tree analysis and a reliability centered maintenance (RCM) program.

(2) Qualitative method is used when no known failure rates and failure modes are available. The criticality or risk associated with each failure is subjectively classified by the team members. The use of a subjective ranking system is applied to the severity, and occurrence of the failures. This method will provide a relative ranking of item failure mode's effects for identifying areas of concern and for initiating other analyses such as RCM, fault tree, and logistics. As the system matures it is recommended that data be collected to enhance the analysis through a quantitative method.

4-3. Transfer select data from FMEA sheet

The information from the FMEA sheet that will be used in the FMECA worksheet will aid in developing the criticality analyses. Given the fact that not all of the information will be shown on the FMECA sheet, does not mean that the excluded information will be ignored. The FMEA sheet will still be referenced frequently for data.

a. The major contributing factors for not including all of the information are space and clarity. All of the information on the FMEA can sometimes be difficult to read by its own not to mention if it is combined with both analyses on one document. This is just a suggestion that may or may not be desirable at every facility. In fact some facilities may choose to add more categories. Keep in mind, this manual is just a guide and is meant to be flexible in order to achieve the objective of the analysis.

b. Once it is determined which type of analysis will be conducted, qualitative or quantitative, the appropriate FMECA worksheet can be chosen. Examples of FMECA sheets for the two different types of analyses are provided in figures 4-2 and 4-3.

c. The following categories will be transferred from the FMEA sheet:

(1) Item Number

(2) Item/Functional ID

(3) Failure Modes

(4) Failure Mechanisms

(5) Failure Effects (qualitative only due to space limitations)

(6) Severity Classification/Ranking

d. All other categories from the FMEA will be referenced during the criticality analysis.

4-4. Quantitative criticality analysis

Once it is determined that sufficient failure rate data and failure mode distributions are available, a criticality worksheet for conducting a quantitative analysis that looks like figure 4-2 will be used. Note that some of the categories are derived from the FMEA sheet. The additional categories will be used to calculate the criticality number. Traditional methods will be used to derive this number except where redundant components are used, which is typical with a C4ISR facility. The required amount of components necessary (M) to perform the function and the amount of components that are redundant (N) should be recorded. The effect of redundancy will be discussed in paragraph 4-5. A description of each category and variable used in the CA is listed below.

a. Beta (β) is defined as the failure effect probability and is used to quantify the described failure effect for each failure mode indicated in the FMECA. The beta (β) values represent the conditional probability or likelihood that the described failure effect will result in the identified criticality classification, given that the failure mode occurs. The β values represent the analyst's best *judgment* as to the likelihood that the loss or end effect will occur. For most items the failure effect probability (β) will be 1. An example would be if the generator engine shuts down (failure mode), we can confidently state that 100% of the time the effect will be loss of power.

(1) However, if the failure mode was that *the generator produces low voltage* (brown out condition), the end effect could vary. Effects such as *degraded motor function* or *motor burns up* condition on various pieces of equipment could occur. Therefore there are two possible effects for the generator's failure mode *low voltage*; *degraded motor function* and *motor burns up.*

(2) Now the analyst must make a judgment call of what percentage of time or probability each effect may occur. If the analyst determined that 80% of the time the *motor is degraded*, then beta (β) for that effect would be (.80). This would leave 20% of the time the effect would be *motor burns up* and would be assigned a beta (β) of (.20).

b. Alpha (α) is the probability, expressed as a decimal fraction, that the given part or item will fail in the identified mode. If all of the potential failure modes for a device are considered, the sum of the alphas will equal one. Determining alpha is done as a two part process for each component being analyzed. First, the failure modes are determined and secondly, modal probabilities are assigned.

(1) Modal failures represent the different ways a given part is known, or has been "observed", to fail. It is important to make the distinction that a failure mode is an "observed" or "external" effect so as not to confuse failure mode with failure mechanism. A failure mechanism is a physical or chemical process flaw caused by design defects, quality defects, part misapplication, wear out, or other processes. It describes the basic reason for failure or the physical process by which deterioration proceeds to failure.

(2) For example, when there is no air flow from an air handling unit caused by a broken belt. In this example, the failure mode would be the "no air flow from air handling unit" while the failure mechanism would be the "broken belt". Another failure mode could be low air flow and the mechanism would be belt slippage (loose belt).

(3) Once common part failure modes have been identified, modal probabilities (α) are assigned to each failure mode. This number represents the percentage of time, in decimal format, that the device is expected to fail in that given mode. This number is statistically derived and is given as a percentage of the total observed failures. Using the air handler example, the probabilities of occurrence for each failure mode are shown in table 4-1.

Table 4-1. Failure mode ratio (α)

Part Failure Modes	**Failure Mode Ratio (α)**
Blows too little air	0.55 or 55%
Blows too much air	0.05 or 5%
Blows no air	0.40 or 40%
The sum of the modal probabilities is	1.00 or 100%

Note: These are hypothetical failure mode ratios.

(4) Alpha and beta are commonly confused. It is best to memorize that alpha is the failure mode ratio, the percentage of time how or in what manner an item is going to fail. However, beta is the conditional probability of a failure effect occurring given a specific failure mode; when a failure mode occurs, what percentage of time is this going to be the end effect. Beta typically is assigned 1 in order to only consider the worst possible end effect as a result of a failure mode.

c. The failure rate (λ_p) of an item is the ratio between the numbers of failures per unit of time and is typically expressed in failures per million hours or failures/10^6 hours. Although failure data compiled from actual field test are recommended, other sources for failure information are available for use until actual field data can be obtained. These sources are mentioned in appendix B.

(1) When analyzing system failure rates where redundant like components are used to accomplish a mission, the failure rate must be adjusted to reflect the “system failure rate”. This is explained in paragraph 4-5. When entering in the failure rate on the FMECA sheet, in parentheses you should identify that the failure rate is the single item component failure rate or the failure rate of the redundant system. The example at the end of this section provides an example of how to show this. It indicates the single failure rate and the redundant failure rate.

(2) The source of the failure rate should also be noted in this category as well so that anyone who looks at the analysis will know if the data was derived by field data or some other source for reference purposes. This will be important if someone does question the validity of the data.

d. The modal failure rate is the fraction of the item's total failure rate based on the probability of occurrence of that failure mode. The sum of the modal failure rates for an item will equal the total item failure rate providing all part failure modes are accounted for. If there are three different failure modes, then all three failure rates (modal failure rates) will equal the item failure rate. The modal failure rate is given by the equation:

$$\lambda_m = \alpha \lambda_p \qquad \text{(Equation 4-1)}$$

where:

λ_m = the modal failure rate
α = the probability of occurrence of the failure mode (failure mode ratio)
λ_p = the item failure rate

e. Failure mode (modal) criticality number. The failure mode criticality number is a relative measure of the frequency of a failure mode. In essence it is a mathematical means to provide a number in order to rank importance based on its failure rate. The equation used to calculate this number is as follows:

$$C_m = (\beta \alpha \lambda_p t) \qquad \text{(Equation 4-2)}$$

where:

C_m = Failure mode criticality number
β = Conditional probability of the current failure mode's failure effect
α = Failure mode ratio
λp = Item failure rate
t = Duration of applicable mission phase (expressed in hours or operating cycles)

(1) This number is derived from the modal failure rate which was explained in paragraph 4-4d. It also takes into consideration of the operating time that the equipment or system is running in hours or operating cycles.

(2) Below is an example of a centrifugal pump used for condenser water circulation. The failure rates were derived from the *Non-electric Parts Reliability Data-95* (NPRD-95) publication and the failure mode probability was derived from the *Failure Mode/Mechanism Distribution-97* (FMD-97) publication. The failure effect probability (β) will equal 1.

Failure mode criticality:

Component type: Centrifugal pump condenser circulation

Part number: P1

Failure rate (λp): 12.058 failures per million hours

Source: NPRD-95

Failure Mode probability (α):
No output (0.29)
Degraded (0.71)
Source: FMD-97
Time (t): 1 hour

Failure effect probability (β): 1

Failure mode criticality (C_m):

$$C_m = \beta \alpha \lambda_p t$$

C_m (No output) = (1 x .29 x 12.058 x 1)
C_m (No output) = 3.5 x 10^{-6}

C_m (Degraded) = (1 x .71 x 12.058 x 1)
C_m (Degraded) = 8.56 x 10^{-6}

f. Item criticality number. The item criticality number is a relative measure of the consequences and frequency of an item failure. This number is determined by totaling all of the failure mode criticality numbers of an item *with the same severity level*. The severity level was determined in the FMEA. The equation used to calculate this number is as follows:

$$C_r = \sum(C_m) \qquad \text{(Equation 4-3)}$$

where:

C_r = Item criticality number
C_m = Failure mode criticality number

(1) If an item has three different failure modes, two of which have a severity classification of 3 and one with a classification of 5, the sum of the two "failure mode criticality numbers" (C_m) with the severity classification of 3 would be one "item criticality number" (C_r). The failure mode with the severity classification of 5 would have an "item criticality number" equal to its "failure mode criticality number".

(2) The example below was used in the failure mode criticality example. Both failure modes for this example have the same severity classification of 3. If the severity classifications were different, then the item criticality numbers would be calculated as separate items. In this case, since there are only two failure modes, the item criticality number for each severity level would equal the failure mode criticality number.

Item criticality:
Component type: Centrifugal pump condenser circulation

Part Number: P1

Failure rate (λp): 12.058 failures per million hours
Source: NPRD-95

Failure mode probability (α):
No output (0.29)
Degraded (0.71)
Source: FMD-97

Time (t): 1 hour

Failure effect probability (β): 1

Item criticality (Cr):

$$C_r = \sum_{n=1}^{j} \left(\beta\alpha\lambda_p t\right)_n \quad n = 1, 2, 3 \ldots j \text{ or } C_r = \sum_{n=1}^{j} (C_m)\ n$$

$$C_r = (1 \text{ x } .29 \text{ x } 12.058 \text{ x } 1) + (1 \text{ x } .71 \text{ x } 12.058 \text{ x } 1)$$

$$C_r = 12.058$$

4-5. Effects of redundancy – quantitative

When redundancy is employed to reduce system vulnerability and increase uptime, failure rates need to be adjusted prior to using the preceding formula. This can be accomplished by using formulas from various locations depending on the application. Below is a few examples from the *Reliability Toolkit: Commercial Practices Edition*, page 161, which is based on an exponential distribution of failure (constant time between failures).

a. Example 1: For a redundant system where all units are active "on-line" with equal failure rates and (n-q) out of n required for success. This equation takes repair time into consideration.

$$\lambda_{(n-q)/n} = \frac{n!(\lambda)^{q+1}}{(n-q-1)!(\mu)^q}, \text{ with repair} \qquad \text{(Equation 4-4)}$$

where:

n = number of active on line units; n! is n factorial.
λ = failure rate for on-line unit (failures/hour)
q = number of online units that can fail without system failure
μ = repair rate (μ=1/MTTR; where MTTR is the mean time to repair (hour).

b. Therefore, if a system has five active units, each with a failure rate of 220 f/10^6 hours, and only three are required for successful operation. If one unit fails, it takes an average of three hours to repair it to an active state. What is the effective failure rate of this configuration?

c. Substituting the following values into the equation:

$$n = 5,\ q = 2,\ \mu = 1/3$$

$$\lambda_{(5-2)/5} = \lambda_{3/5}$$

$$\lambda_{3/5} = \frac{5!(220x10^{-6})^3}{(5-2-1)!(1/3)^2} = 5.75x10^{-9} \text{ failures/hour}$$

$$\lambda_{3/5} = .00575 \text{ failures}/10^6 \text{ hours}$$

d. Then this new failure rate ($\lambda_{3/5}$) would be substituted for (λ_p) to determine criticality numbers of the system.

e. Example 2**:** If by chance in the above sample, the unit was never repaired then the formula to use would be:

$$\lambda_{(n-q)/n} = \frac{\lambda}{\sum_{i=n-q}^{n} \frac{1}{i}}, \text{ without repair} \qquad \text{(Equation 4-5)}$$

f. Using the same problem from above and substituting into this formula

$$\lambda_{3/5} = \frac{220x10^{-6}}{\left(\frac{1}{3}\right)+\left(\frac{1}{4}\right)+\left(\frac{1}{5}\right)} = \frac{220x10^{-6}}{\frac{47}{60}}$$

$$\lambda_{3/5} \approx 280x10^{-6} \text{ failures/hour}$$

$$\lambda_{3/5} \approx 280 \text{ failures}/10^6 \text{ hours}$$

g. A noticeable increase in failure rate due to the fact that the components are not repaired!

h. Other useful failure rate formulas used for redundant systems are as follows:

i. Example 3 & 4**:** One standby off-line unit with n active on-line units required for success. Off-line spare assumed to have a failure rate of zero. On-line units have equal failure rates.

$$\lambda_{n/n+1} = \frac{n[n\lambda + (1-P)\mu]\lambda}{\mu + n(P+1)\lambda}, \text{ with repair} \qquad \text{(Equation 4-6)}$$

$$\lambda_{n/n+1} = \frac{n\lambda}{P+1}, \text{ without repair} \qquad \text{(Equation 4-7)}$$

where:

n	=	number of active on line units; n! is n factorial.
λ	=	failure rate for on-line unit (failures/hour)
q	=	number of online units that can fail without system failure
μ	=	repair rate (μ=1/MTTR; where MTTR is the mean time to repair (hr).
P	=	probability that the switching mechanism will operate properly when needed (P=1 with perfect switching)

j. Example 5 & 6**:** Two active on-line units with different failure and repair rates. One of two is required for success.

$$\lambda_{1/2} = \frac{\lambda_A \lambda_B \left[(\mu_A + \mu_B) + (\lambda_A + \lambda_B)\right]}{(\mu_A)(\mu_B) + (\mu_A + \mu_B)(\lambda_A + \lambda_B)} \text{, with repair} \qquad \text{(Equation 4-8)}$$

$$\lambda_{1/2} = \frac{\lambda_A{}^2 \lambda_B + \lambda_A \lambda_B{}^2}{\lambda_A{}^2 + \lambda_B{}^2 + \lambda_A \lambda_B} \text{, without repair} \qquad \text{(Equation 4-9)}$$

k. These new failure rates (λ) should then be placed back in the equation, $Crc = \sum_{n=1}^{j} (\beta\alpha\lambda pt)n$, to calculate the new Criticality Number which accounts for redundancy.

l. If your particular situation is not addressed in the preceding formulas, there is a technical publication that exclusively addresses various redundancy situations that may be of use, Rome Air Development Center, RADC-TR-77-287, *A Redundancy Notebook*, Rome Laboratory, 1977.

m. If the facility does have failure rate data but does not have failure mode distribution data, a relative ranking can still be achieved, allowing for redundancy, by using the method described in the qualitative analysis.

4-6. Qualitative criticality analysis

Qualitative analysis will be used when specific part or item failure rates are not available. However, if failure rates are known on some components and not known on others, the failure rate data can be used to support the rankings below. This will provide a relative ranking between all of the components. Failure mode ratio and failure mode probability are not used in this analysis. This analysis will allow the analysts the ability to subjectively rank each failure modes level of severity in relationship to its probability of failure. The items of most concern will be identified and evaluated in order to decrease the negative impact on the mission.

a. Once it is determined that a qualitative approach will be used the Criticality worksheet that looks like figure 4-3 will be used. Note that some of the categories are derived from the FMEA sheet. The information from the FMEA should be transferred into the respective columns of the criticality worksheet. The additional categories will be used to support and calculate the Risk Priority Number (RPN), which will be explained in paragraph 4-6g. Adjustments to occurrence rankings to compensate for redundant components within a typical C4ISR facility must be addressed as well and will be discussed in paragraph 4-7.

Therefore, it is essential that the required amount of components necessary (M) to perform the function and the amount of components that are redundant (N) should be recorded in the respective categories of the criticality worksheet. Figure 4-5 is an example of the quantitative FMECA worksheet with redundant components.

QUANTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System — DATE (YYYYMMDD): 20050819

PART NAME: Industrial Water Supply — SHEET: 1 of: 3

REFERENCE DRAWING: — COMPILED BY: AAA

MISSION: Provide Temperature Control to Room — APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNCTIONAL ID	POTENTIONAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	SEVERITY	REDUNDANCY HAVE (N)	REDUNDANCY NEED (M)	FAILURE RATE λ_p (SOURCE)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (C_M)	ITEM CRITICALITY NUMBER (ΣC_M)	REMARKS
110.0	Reservoir/contain 6000 gallons of water	Leak	Crack in wall, Ruptured drain pipe	4	2	1	1.500x10-6 (single) NPRD-95 .0104x10-6 (redundant)	1	1	61,320	6.38 x10-4	6.38 x10-4	
120.0	Pump #1/ Transport industrial water at 1000GPM	Transport water at a rate below 1000GPM	impeller degraded, gasket leak, motor degraded	3	4	1	12.058x10-6 (single) NPRD-95 1.4x10-17 (redundant)	1	.35	61,320	3.00x10-13	8.58x10-13	
120.1		produce no water flow	broken coupling, suction line leak, motor inoperable	3				1	.65	61,320	5.58x10-13		
130.0	Cooling Tower #1/ maintain a water temp of 75°F.	Scaling (deposits) on media	Untreated water	4	4	1	10.0518x10-6 (single) NPRD-95 1.3x10-16 (redundant)	1	.36	61,320	2.87x10-12	6.38x10-12	
130.1		Clogged sprayers	Untreated / unfiltered water	4				1	.44	61,320	3.51x10-12		

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Figure 4-5. Example of DA Form 7611, Quantitative FMECA with redundant components

QUANTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System

PART NAME: Industrial Water Supply

REFERENCE DRAWING:

MISSION: Provide Temperature Control to Room

DATE *(YYYYMMDD)*: 20050819

SHEET: 2 of: 3

COMPILED BY: AAA

APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNC-TIONAL ID	POTENTIONAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	SEVER-ITY	REDUNDANCY		FAILURE RATE λ_p (SOURCE)	FAILURE EFFECT PROBAB-ILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (C_M)	ITEM CRITICALITY NUMBER (ΣC_M)	REMARKS
					HAVE (N)	NEED (M)							
130.2		Fan failure	Motor winding open, No voltage to motor	3				1	.2	61,320	1.54x10-12	1.54x10-12	
210.0	Pump #5/ Transport chilled-water supply 960GPM	Degraded operation-produce water at less than 960GPM	impeller degraded, gasket leak, motor degraded	3	2	1	12.058x10-6 (single) NPRD-95 8.72x10-10 (redundant)	1	.35	61,320	3.00x10-13	8.58x10-13	
210.1		produce no water flow	broken coupling, suction line leak, motor inoperable	3				1	.65	61,320	5.58x10-13		
220.0	Chiller/ Remove heat(10°F) from chilled water	Degraded operation-remove less than 10°F	refrig. leak, degraded comp., tube leak, dirty coil	3	2	1	9.2791x10-6 (single) NPRD-95 1.72x10-10 (redundant)	1	.92	61,320	9.70 x10-6	9.70 x10-6	
220.1		remove no heat	compressor seizure, motor failure	4				1	.08	61,320	8.45 x10-6	8.45 x10-6	Expensive and time consuming to repair

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Figure 4-5. Example of DA Form 7611, Quantitative FMECA with redundant components (cont'd)

QUANTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System

PART NAME: Industrial Water Supply

REFERENCE DRAWING:

MISSION: Provide Temperature Control to Room

DATE (YYYYMMDD): 20050819

SHEET: 3 of: 3

COMPILED BY: AAA

APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNCTIONAL ID	POTENTIONAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	SEVERITY	REDUNDANCY		FAILURE RATE λ_p (SOURCE)	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	OPERATING TIME (t)	FAILURE MODE CRITICALITY NUMBER (C_M)	ITEM CRITICALITY NUMBER (ΣC_M)	REMARKS
					HAVE (N)	NEED (M)							
310.0	Air Handler/ Maintain room temp of 72°F, 3200cfm	Maintain air temp higher than 72°F	Dirty coils	3	2	1	1.7657x10-6 (single) NPRD-95 6.24x10-12 (redundant)	1	.35	61,320	1.34 x10-7	3.826x10-7	
310.1		Provide air flow at a rate less than 3200cfm	reduced motor output, Dirty intake filter	3				1	.40	61,320	1.53 x10-7		
310.2		Provide no air flow	broken belt, motorfailure, fan bearing seizure, No AC power	3				1	.25	61,320	9.56 x10-8		

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Figure 4-5. Example of DA Form 7611, Quantitative FMECA with redundant components (cont'd)

b. The occurrence ranking is a method used to subjectively assign a failure rate to a piece of equipment or component. Each step in the ranking will correspond to an estimated failure rate based on the analyst's experience with similar equipment used in a similar environment. As mentioned previously, a known failure rate can be cross referenced to an occurrence ranking thereby allowing a complete analysis of a system that does not have failure rate and failure mode information on every item or component. When known failure rate data is used in this type of analysis, it not only adds merit to the ranking for the equipment with failure data, but also adds merit to the occurrence rankings of unknown equipment by providing benchmarks within the ranking scale. These values will establish the qualitative failure probability level for entry into a CA worksheet format. Adjust the failure rates for your particular application. Rates can be hours, days, cycles …etc.

c. Possible qualitative occurrence rankings (O) are shown in Table 4-2.

Table 4-2. Occurrence rankings

Ranking	Failure Rate	Comment
1	1/10,000	Remote probability of occurrence; unreasonable to expect failure to occur
2	1/5,000	Very low failure rate. Similar to past design that has, had low failure rates for given volume/loads
3	1/2,000	Low failure rate based on similar design for given volume/loads
4	1/1,000	Occasional failure rate. Similar to past design that has had similar failure rates for given volume/loads.
5	1/500	Moderate failure rate. Similar to past design having moderate failure rates for given volume/loads.
6	1/200	Moderate to high failure rate. Similar to past design having moderate failure rates for given volume/loads.
7	1/100	High failure rate. Similar to past design having frequent failures that caused problems
8	1/50	High failure rate. Similar to past design having frequent failures that caused problems
9	1/20	Very high failure rate. Almost certain to cause problems
10	1/10+	Very high failure rate. Almost certain to cause problems

d. The severity ranking, as mentioned in paragraph 3-9, is also important in determining relative concerns amongst failure modes. The severity of the consequences of the failure effect is evaluated in terms of worst potential consequences upon the system level which may result from item failure. A severity classification must be assigned to each system level effect. A lower ranking indicates a less severe failure effect. A higher ranking indicates a more severe failure effect. Severity classifications provide a qualitative measure of the worst potential consequences resulting from an item failure

e. The severity rankings (S) from table 3-1 are again shown here in table 4-3.

Table 4-3. Severity rankings

Ranking	Effect	Comment
1	None	No reason to expect failure to have any effect on Safety, Health, Environment or Mission
2	Very Low	Minor disruption t facility function. Repair to failure can be accomplished during trouble call.
3	Low	Minor disruption t facility function. Repair to failure may be **longer** than trouble call but does not delay Mission.
4	Low to Moderate	Moderate disruption to facility function. Some portion of Mission may need to be reworked or process delayed.
5	Moderate	Moderate disruption to facility function. **100%** of Mission may need to be reworked or process **delayed**.
6	Moderate to High	Moderate disruption to facility function. Some portion of Mission is lost. **Moderate** delay in restoring function.
7	High	High disruption to facility function. Some portion of Mission is lost. **Significant** delay in restoring function.
8	Very High	High disruption to facility function. **All** of Mission is lost. Significant delay in restoring function.
9	Hazard	Potential Safety, Health or Environmental issue. Failure will occur **with** warning.
10	Hazard	Potential Safety, Health or Environmental issue. Failure will occur **without** warning

f. The Risk Priority Number (RPN) is the product of the Severity (1-10) and the Occurrence (1-10) ranking.

$$\text{RPN} = (\text{S}) \times (\text{O}) \qquad \text{(Equation 4-10)}$$

g. The Risk Priority Number is used to rank and identify the concerns or risks associated with the operation due to the design. This number will provide a means to prioritize which components should be evaluated by the team in order to reduce their calculated risk through some type of corrective action or maintenance efforts. *However, when severity is at a high level, <u>immediate</u> corrective action may be given <u>regardless</u> of the resultant RPN.*

h. This method was developed by the Automotive Industry Action Group (AIAG) and can be found in the reference manual titled *Potential Failure Mode and Effects Analysis – FMEA*. However, this manual also considers detection to determine the Risk Priority Number.

$$\text{RPN} = (\text{S}) \times (\text{O}) \times (\text{D}) \qquad \text{(Equation 4-11)}$$

i. Where *detection* is ranked (1-10), shown in table 4-4, in a similar fashion as *severity* and *occurrence*;

Table 4-4. Detection rankings

Ranking	Detection	Comment
1	Almost Certain	Current control(s) almost certain to detect failure mode. Reliable controls are known with similar processes.
2	Very High	Very high likelihood current control(s) will detect failure mode
3	High	High likelihood current control(s) will detect failure mode
4	Moderately High	Moderately high likelihood current control(s) will detect failure mode
5	Moderate	Moderate likelihood current control(s) will detect failure mode
6	Low	Low likelihood current control(s) will detect failure mode
7	Very Low	Very low likelihood current control(s) will detect failure mode
8	Remote	Remote likelihood current control(s) will detect failure mode
9	Very Remote	Very remote likelihood current control(s) will detect failure mode
10	Almost Impossible	No known control(s) available to detect failure mode

j. This variable was not included in the examples because in mission critical facilities, the team considers detection of a failure mode when assigning a severity ranking. They also consider a compensating provision such as redundancy. The end effect is altered due to these two contributing factors, therefore changing the severity of the consequences of this failure by design of the facility.

k. Given the scenario that a compressor overheats due to the lack of lubrication, the effects would be "compressor seizes, room temperature rises, and computers malfunction". This would produce a severity ranking of "7" or "8". But due to the ability of the system to detect a problem, shut down the one component, and activate a redundant component in its place, a severity of "2" or "3" may be assigned for the failure mode. Note that it is also possible that the occurrence ranking will also be altered as well due to the redundant system. Even if there was no redundant component the end effect is altered because the ability to detect and shut down the compressor will prevent it from seizing thus saving repair or replacement costs and shortening the duration of down time by minimizing the damage.

l. In addition, a C4ISR facility has a different "product" than the auto industry. The auto industry is producing parts and the C4ISR facility is producing consistent temperature control and high quality electricity. The auto industry does not want, under any circumstance, to allow a defective part out of their facility. If it does, the consequences would cost them immensely on recalls or warranty work. Therefore it makes sense that they would consider detection of a faulty part prior to leaving their facility as important as severity in their analysis. This is not the case with a C4ISR facility. The system's goal in a C4ISR facility is to be available. Just because you have detected a failure does not necessarily mean that the end level effect is prevented. However, it may minimize the downtime, thus increasing availability. This would be taken into consideration when you assign severity. For that reason, even though detection is considered in classifying severity, it does not hold the same relative importance.

4-7. Effects of redundancy – qualitative

Traditional methods for dealing with redundancy's effect on failure rate are rather lengthy and difficult to apply to a qualitative analysis. Therefore further explanation is required for how we deal with criticality rankings for like components within a single redundant system.

a. For example, consider an occurrence ranking of 9 for a chilled water supply pump (see figure 4-6). In essence, the analysis is ranking the failure rate associated with the loss of function of that component relative to the equipment operation, or mission as a whole, and not the component itself. So, the question becomes "how can we subjectively, but meaningfully, rank like redundant components with the same system function?"

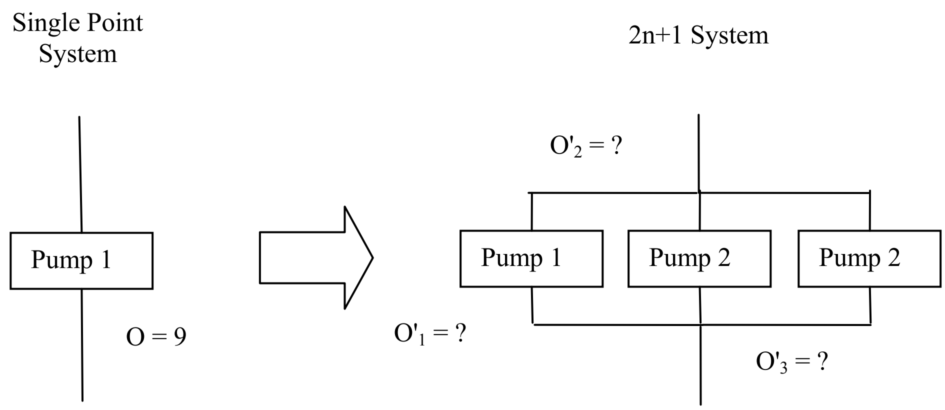

Figure 4-6. Single point system vs. redundant system

b. By design, a redundant system is more reliable and less vulnerable than a single component, with respect to system function and mission requirements. So, it makes sense that qualitative ranking of redundant components should take such concepts as degree of redundancy and presumed individual component reliability into consideration.

c. As a result of decreased system vulnerability, each individual component is less critical to the system function and mission requirement. Therefore, it is evident that O'_1, O'_2, and O'_3 should not all have the same ranking number as the single component system (9). Furthermore, the relationship between degree of redundancy and occurrence is not linear. So, it is also evident that the value for O'_1, O'_2, and O'_3 cannot be a strict division by n of the ranking number assigned to the redundant system's function (3, 3, and 3). This is supported with the redundancy formula in the quantitative criticality analysis paragraph (4-5a equation 4-4).

d. The occurrence ranking number for a single component function must be weighted to reflect the operation, presumed reliability, and severity of loss of function of the redundant component system as accurately as possible. Furthermore, it should be observed that for mission critical facilities, the presence of one more component than needed is not sufficient to confidently assure mission availability. Therefore, a conservative factor should also be observed when determining individual occurrence rankings of redundant components, relative to the single point function.

e. The following mathematical equations can be used to emulate a non-linear redundancy/occurrence relationship while introducing a conservative mission critical factor:

$$O' = O \times \frac{M}{N-1} \qquad \text{(Equation 4-12)}$$

where:

O	=	Occurrence level for loss of subsystem / system function
O'	=	The adjusted occurrence level for the current redundant component being analyzed
M	=	The minimum number of components necessary
N	=	The number of components available

f. Note that using this formula with only 1 redundant component will result in an occurrence ranking equal to the original. This formula reinforces the importance of having at least one extra component than necessary in a mission critical facility. The only way to decrease the occurrence ranking is to have 2 or more additional components than required.

$$O' = O \times \frac{M}{N-1}$$

Using:

$$M=2$$
$$N=3$$
$$O' = O \times \frac{2}{3-1}$$
$$O' = O \times \frac{2}{2}$$
$$O' = O \times 1$$

where:

O	=	Occurrence level for loss of subsystem / system function
M	=	The minimum number of components necessary
N	=	The number of components available
O'	=	The adjusted occurrence level for the current redundant component

g. Likewise, if only 2 items are needed and 4 are available and the occurrence is 9:

$$M=2$$
$$N=4$$
$$O' = O \times \frac{2}{4-1}$$
$$O' = 9 \times \frac{2}{3}$$
$$O' = 6$$

h. Insert O' into the equation $RPN = O' \times S$ using the new severity ranking due to the fact that the consequences of a failure of one component is not as severe to the end failure effect.

Original: $RPN = O \times S = 9 \times 8 = 72$

New: $RPN = O' \times S = 6 \times 5 = 30$

i. When sufficient failure rate data is available it is always recommended that quantitative criticality analysis be conducted through calculation or modeling. However, when a complete and detailed quantitative analysis is not necessary, realistically feasible, or desirable, the use of equation 4-12 can be incorporated to quickly emulate the redundancy/occurrence relationship as part of a qualitative analysis.

j. This “combined” method allows for an analysis to be conducted using the qualitative (subjective) approach and also using supportive data to rank occurrence. Ranking occurrence with supportive data not only provides more merit to the results but offers flexibility by allowing the analyst to use data for components when available in the same analysis as other components that may not have any supportive data.

k. This is accomplished by allowing the failure rate (λ), failure mode probability (α), and the failure effect probability (β) to be multiplied to determine a failure rate for a particular failure mode. This rate can then be cross referenced in the occurrence ranking chart and assigned a new ranking (O'). Substituting in the formula:

$$\mathrm{RPN} = (O') \times (S)$$

l. This adjusted RPN will then be used in the final ranking process. Figure 4-7 is an example of a FMECA using the qualitative method utilizing the redundancy formula to adjust the occurrence ranking. After the redundancy formula was applied the number was rounded to the nearest whole number for this example. The components that only had one additional backup component did not have their occurrence rankings altered by this equation. *Note: Rounding is not mandatory. This was done in the example for simplicity.*

QUALTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System

DATE (YYYYMMDD): 20050819

PART NAME: HVAC System

SHEET: 1 of: 3

REFERENCE DRAWING:

COMPILED BY: AAA

MISSION: Provide Temperature Control to Room

APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNC-TIONAL ID	POTENTIONAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	FAILURE EFFECTS	SINGLE COMPONENT			REDUNDANT SYSTEM					REMARKS AND/OR RECOMMENDED ACTIONS
					OCCUR	SEVER-ITY	RPN (O)X(S)	HAVE (N)	NEED (M)	OCCUR	SEVER-ITY	RPN (O')X(S)	
110.0	Reservoir/contain 6000 gallons of water	leak	Crack in wall, Drain pipe breaks	No immediate effect. The surrounding area will be saturated.	2	6	12	2	1	2	4	8	If drain pipe breaks, secondary contain-ment will be filled
120.0	Pump #1/ Transport Industrial water supply at 1000gpm	Transport water at a rate below 1000 gpm	Impeller degradation, gasket leak, motor degraded	No immediate effect. Chiller inefficiency will cost $$.	3	4	12	4	1	1	3	3	
120.1		produce no water flow	Broken coupling, leak on suction line, motor inoperable	Room temp will rise above max allowed temp. Mission failure.	6	5	30	4	1	2	3	6	
130.0	Cooling Tower #1/ maintain a water temp of 75°F.	Scaling (deposits) on media	Untreated water	Room temperature will rise slightly	3	6	18	4	1	1	4	4	
130.1		Clogged sprayers	Untreated / unfiltered water	Room temp will rise, Chiller efficiency decreases	3	5	15	4	1	1	4	4	

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APD V1.00

Figure 4-7. Example of DA Form 7612, FMECA worksheet using qualitative rankings

QUALTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System

PART NAME: HVAC System

REFERENCE DRAWING:

MISSION: Provide Temperature Control to Room

DATE *(YYYYMMDD)*: 20050819

SHEET: 2 of: 3

COMPILED BY: AAA

APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNC-TIONAL ID	POTENTIONAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	FAILURE EFFECTS	SINGLE COMPONENT			REDUNDANT SYSTEM					REMARKS AND/OR RECOMMENDED ACTIONS
					OCCUR	SEVER-ITY	RPN (O)X(S)	HAVE (N)	NEED (M)	OCCUR	SEVER-ITY	RPN (O')X(S)	
130.2		Fan failure	Motor winding open, No power to motor	Air temp rise. No severe effect. Chiller efficiency decreases	3	4	12	4	1	1	3	3	
210.0	Pump #5/ Transport chilled water supply at 960gpm	Degraded operation-pro duce water at a rate less than 960gpm	impeller degraded, gasket leak, motor degraded	No immediate effect. Chiller efficiency decreases. $$$	1	4	4	2	1	1	3	3	
210.1		produce no water flow	broken coupling, leak on suction line, motor inoperable	No air cooling Room temp rise above allowed-Missi on failure	2	8	16	2	1	2	3	6	
220.0	Chiller/ Remove heat(10°F) from chilled water supply	Degraded operation -remove less than 10°F	Refrigerant loss, degraded compressor, leaky tube, dirty coil	Air temperature will rise but not above max allowed	7	6	42	2	1	7	3	21	
220.1		remove no heat	compressor seizure, motor failure	Min. air cooling. Temp above max. Mission failure	2	8	16	2	1	2	4	8	

DA FORM 7612, AUG 2006 APD V1.00

Figure 4-7. Example of DA Form 7612, FMECA worksheet using qualitative rankings (cont'd)

QUALTITATIVE FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS (FMECA)

For use of this form, see TM 5-698-4; the proponent agency is USACE.

SYSTEM: Mechanical System | DATE *(YYYYMMDD)*: 20050819
PART NAME: HVAC System | SHEET: 3 of: 3
REFERENCE DRAWING: | COMPILED BY: AAA
MISSION: Provide Temperature Control to Room | APPROVED BY: BBB

ITEM NUMBER	ITEM/FUNC-TIONAL ID	POTENTIONAL FAILURE MODES	FAILURE MECHANISM (CAUSE)	FAILURE EFFECTS	SINGLE COMPONENT			REDUNDANT SYSTEM					REMARKS AND/OR RECOMMENDED ACTIONS
					OCCUR	SEVER-ITY	RPN (O)X(S)	HAVE (N)	NEED (M)	OCCUR	SEVER-ITY	RPN (O')X(S)	
310.0	Air Handler/ Provide air to room at 72°F, 3200cfm	Provide air at a temp higher than 72°F	Dirty coils	Minimal change in temperature	3	4	12	2	1	3	3	9	
310.1		Provide airflow at a rate less than 3200cfm	reduced motor output , dirty intake filter	Temperature variations in room dependant on location	2	3	6	2	1	2	3	6	
310.2		Provide no air flow	broken belt, motor failure bearing seizure in fan, Loss of power	Temp rise above max allowed. Mission failure	2	7	14	2	1	2	3	6	

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Figure 4-7. Example of DA Form 7612, FMECA worksheet using qualitative rankings (cont'd)